# PLASMA REACTOR AND PROCESS FOR PRODUCING LOWER-ENERGY HYDROGEN SPECIES

This application claims priority to U.S. Application Serial No. 60/462,705, filed April 15, 2004, the complete disclosure of which is incorporated herein by reference.

## I. INTRODUCTION

### 1. Field of the Invention:

This invention relates to a reactor to generate power, plasma, light, and novel hydrogen compounds by the catalysis of atomic hydrogen. The power balance is optimized by maximizing the output power from the hydrogen catalysis reaction while minimizing the input power by controlling the parameters of the input power to initiate or at least partially maintain the plasma such as the power density, pulse frequency, duty cycle, and peak and offset electric fields.

### 2. Background of the Invention

#### 2.1 Hydrinos

A hydrogen atom having a binding energy given by

$$\textit{Binding Energy} = \frac{13.6\ eV}{\left(\frac{1}{p}\right)^2} \tag{1}$$

where $p$ is an integer greater than 1, preferably from 2 to 137, is disclosed in R. Mills, *The Grand Unified Theory of Classical Quantum Mechanics*, January 2000 Edition, BlackLight Power, Inc., Cranbury, New Jersey, (" '00 Mills GUT"), provided by BlackLight Power, Inc., 493 Old Trenton Road, Cranbury, NJ, 08512; R. Mills, *The Grand Unified Theory of Classical Quantum Mechanics*, September 2001 Edition, BlackLight Power, Inc., Cranbury, New Jersey, Distributed by Amazon.com (" '01 Mills GUT"), provided by BlackLight Power, Inc., 493 Old Trenton Road, Cranbury, NJ, 08512; R. Mills, *The Grand Unified Theory of Classical Quantum Mechanics*, January 2004 Edition, BlackLight Power, Inc., Cranbury, New Jersey, (" '04 Mills GUT"), provided by BlackLight Power, Inc., 493 Old Trenton Road, Cranbury, NJ, 08512 (posted at www.blacklightpower.com); R. L. Mills, Y. Lu, M. Nansteel, J. He, A. Voigt, B.

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No. 09/110,678 filed July 7, 1998; Serial No. 09/181,180 filed October 28, 1998; Serial No. 09/008,947 filed January 20, 1998; Serial No. 09/009,837 filed January 20, 1998; Serial No. 08/822,170 filed March 27, 1997; Serial No. 08/592,712 filed January 26, 1996; Serial No. 08/467,051 filed on June 6, 1995; Serial No. 08/416,040 filed on April 3, 1995; Serial No. 08/467,911 filed on June 6, 1995; Serial No. 08/107,357 filed on August 16, 1993; Serial No. 08/075,102 filed on June 11, 1993; Serial No. 07/626,496 filed on December 12,1990; Serial No. 07/345,628 filed April 28, 1989; Serial No. 07/341,733 filed April 21, 1989; and U.S. Patent No. 6,024,935; the entire disclosures of which are all incorporated herein by reference; (hereinafter "Mills Prior Publications").

The binding energy of an atom, ion, or molecule, also known as the ionization energy, is the energy required to remove one electron from the atom, ion or molecule. A hydrogen atom having the binding energy given in Eq. (1) is hereafter referred to as a hydrino atom or hydrino. The designation for a hydrino of radius $\frac{a_H}{p}$,where $a_H$ is the radius of an ordinary hydrogen atom and $p$ is an integer, is $H\left[\frac{a_H}{p}\right]$. A hydrogen atom with a radius $a_H$ is hereinafter referred to as "ordinary hydrogen atom" or "normal hydrogen atom." Ordinary atomic hydrogen is characterized by its binding energy of 13.6 eV.

## 2.2 Catalysts

Catalysts of the present invention to generate power, plasma, light such as high energy light, extreme ultraviolet light, and ultraviolet light, and novel hydrogen species and compositions of matter comprising new forms of hydrogen via the catalysis of atomic hydrogen are disclosed in "Mills Prior Publications". Hydrinos are formed by reacting an ordinary hydrogen atom with a catalyst having a net enthalpy of reaction of about

$$m \cdot 27.2\ eV \tag{2a}$$

where $m$ is an integer. This catalyst has also been referred to as an energy hole or source of energy hole in Mills earlier filed Patent Applications. It is believed that the rate of catalysis is increased as the net enthalpy of reaction is more closely matched to $m \cdot 27.2\ eV$. It has been found that catalysts having a net enthalpy of reaction within $\pm 10\%$, preferably $\pm 5\%$, of $m \cdot 27.2\ eV$ are suitable for most applications.

In another embodiment, the catalyst to form hydrinos has a net enthalpy of

reaction of about

$$m/2 \cdot 27.2\ eV \qquad (2b)$$

where $m$ is an integer greater that one. It is believed that the rate of catalysis is increased as the net enthalpy of reaction is more closely matched to $m/2 \cdot 27.2\ eV$. It has been found that catalysts having a net enthalpy of reaction within $\pm 10\%$, preferably $\pm 5\%$, of $m/2 \cdot 27.2\ eV$ are suitable for most applications. The catalyst may comprise at least one molecule selected from the group of $C_2$, $N_2$, $O_2$, $CO_2$, $NO_2$, and $NO_3$ and/or at least one atom or ion selected from the group of Li, Be, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Kr, Rb, Sr, Nb, Mo, Pd, Sn, Te, Cs, Ce, Pr, Sm, Gd, Dy, Pb, Pt, Kr, $2K^+$, $He^+$, $Na^+$, $Rb^+$, $Sr^+$, $Fe^{3+}$, $Mo^{2+}$, $Mo^{4+}$, $In^{3+}$, $He^+$, $Ar^+$, $Xe^+$, $Ar^{2+}$ and $H^+$, $Ne^+$ and $H^+$, $Ne_2*$, $He_2*$, $2H$, and $H(1/p)$.

2.3 Hydrinos

Novel hydrogen species and compositions of matter comprising new forms of hydrogen formed by the catalysis of atomic hydrogen are disclosed in "Mills Prior Publications". The novel hydrogen compositions of matter comprise:

(a) at least one neutral, positive, or negative hydrogen species (hereinafter "increased binding energy hydrogen species") having a binding energy

(i) greater than the binding energy of the corresponding ordinary hydrogen species, or

(ii) greater than the binding energy of any hydrogen species for which the corresponding ordinary hydrogen species is unstable or is not observed because the ordinary hydrogen species' binding energy is less than thermal energies at ambient conditions (standard temperature and pressure, STP), or is negative; and

(b) at least one other element. The compounds of the invention are hereinafter referred to as "increased binding energy hydrogen compounds".

By "other element" in this context is meant an element other than an increased binding energy hydrogen species. Thus, the other element can be an ordinary hydrogen species, or any element other than hydrogen. In one group of compounds, the other element and the increased binding energy hydrogen species are neutral. In another group of compounds, the other element and increased binding energy hydrogen species are charged such that the other element provides the balancing charge to form a neutral

compound. The former group of compounds is characterized by molecular and coordinate bonding; the latter group is characterized by ionic bonding.

Also provided are novel compounds and molecular ions comprising

(a) at least one neutral, positive, or negative hydrogen species (hereinafter "increased binding energy hydrogen species") having a total energy

(i) greater than the total energy of the corresponding ordinary hydrogen species, or

(ii) greater than the total energy of any hydrogen species for which the corresponding ordinary hydrogen species is unstable or is not observed because the ordinary hydrogen species' total energy is less than thermal energies at ambient conditions, or is negative; and

(b) at least one other element.

The total energy of the hydrogen species is the sum of the energies to remove all of the electrons from the hydrogen species. The hydrogen species according to the present invention has a total energy greater than the total energy of the corresponding ordinary hydrogen species. The hydrogen species having an increased total energy according to the present invention is also referred to as an "increased binding energy hydrogen species" even though some embodiments of the hydrogen species having an increased total energy may have a first electron binding energy less that the first electron binding energy of the corresponding ordinary hydrogen species. For example, the hydride ion of Eq. (3) for $p = 24$ has a first binding energy that is less than the first binding energy of ordinary hydride ion, while the total energy of the hydride ion of Eq. (3) for $p = 24$ is much greater than the total energy of the corresponding ordinary hydride ion.

Also provided are novel compounds and molecular ions comprising

(a) a plurality of neutral, positive, or negative hydrogen species (hereinafter "increased binding energy hydrogen species") having a binding energy

(i) greater than the binding energy of the corresponding ordinary hydrogen species, or

(ii) greater than the binding energy of any hydrogen species for which the corresponding ordinary hydrogen species is unstable or is not observed because the ordinary hydrogen species' binding energy is less than thermal energies at ambient conditions or is negative; and

(b) optionally one other element. The compounds of the invention are hereinafter

referred to as "increased binding energy hydrogen compounds".

The increased binding energy hydrogen species can be formed by reacting one or more hydrino atoms with one or more of an electron, hydrino atom, a compound containing at least one of said increased binding energy hydrogen species, and at least one other atom, molecule, or ion other than an increased binding energy hydrogen species.

Also provided are novel compounds and molecular ions comprising

(a) a plurality of neutral, positive, or negative hydrogen species (hereinafter "increased binding energy hydrogen species") having a total energy

(i) greater than the total energy of ordinary molecular hydrogen, or

(ii) greater than the total energy of any hydrogen species for which the corresponding ordinary hydrogen species is unstable or is not observed because the ordinary hydrogen species' total energy is less than thermal energies at ambient conditions or is negative; and

(b) optionally one other element. The compounds of the invention are hereinafter referred to as "increased binding energy hydrogen compounds".

In an embodiment, a compound is provided, comprising at least one increased binding energy hydrogen species selected from the group consisting of (a) hydride ion having a binding energy according to Eq. (3) that is greater than the binding of ordinary hydride ion (about 0.8 eV) for $p = 2$ up to 23, and less for $p = 24$ ("increased binding energy hydride ion" or "hydrino hydride ion"); (b) hydrogen atom having a binding energy greater than the binding energy of ordinary hydrogen atom (about 13.6 eV) ("increased binding energy hydrogen atom" or "hydrino"); (c) hydrogen molecule having a first binding energy greater than about 15.3 eV ("increased binding energy hydrogen molecule" or "dihydrino"); and (d) molecular hydrogen ion having a binding energy greater than about 16.3 eV ("increased binding energy molecular hydrogen ion" or "dihydrino molecular ion").

According to the present invention, a hydrino hydride ion ($H^-$) having a binding energy according to Eq. (3) that is greater than the binding of ordinary hydride ion (about 0.8 eV) for $p = 2$ up to 23, and less for $p = 24$ ($H^-$) is provided. For $p = 2$ to $p = 24$ of Eq. (3), the hydride ion binding energies are respectively 3, 6.6, 11.2, 16.7, 22.8, 29.3, 36.1, 42.8, 49.4, 55.5, 61.0, 65.6, 69.2, 71.6, 72.4, 71.6, 68.8, 64.0, 56.8, 47.1, 34.7, 19.3, and 0.69 eV. Compositions comprising the novel hydride ion are also provided.

The binding energy of the novel hydrino hydride ion can be represented by the following formula:

$$\textit{Binding Energy} = \frac{\hbar^2\sqrt{s(s+1)}}{8\mu_e a_0^2\left[\frac{1+\sqrt{s(s+1)}}{p}\right]^2} - \frac{\pi\mu_0 e^2\hbar^2}{m_e^2}\left(\frac{1}{a_H^3} + \frac{2^2}{a_0^3\left[\frac{1+\sqrt{s(s+1)}}{p}\right]^3}\right) \tag{3}$$

where $p$ is an integer greater than one, $s = 1/2$, $\pi$ is pi, $\hbar$ is Planck's constant bar, $\mu_o$ is the permeability of vacuum, $m_e$ is the mass of the electron, $\mu_e$ is the reduced electron mass given by $\mu_e = \frac{m_e m_p}{\frac{m_e}{\sqrt{\frac{3}{4}}} + m_p}$ where $m_p$ is the mass of the proton, $a_H$ is the radius of the hydrogen atom, $a_o$ is the Bohr radius, and $e$ is the elementary charge. The radii are given by

$$r_2 = r_1 = a_0\left(1+\sqrt{s(s+1)}\right) \quad s = \frac{1}{2} \tag{4}$$

The hydrino hydride ion of the present invention can be formed by the reaction of an electron source with a hydrino, that is, a hydrogen atom having a binding energy of about $\frac{13.6\ eV}{n^2}$, where $n = \frac{1}{p}$ and $p$ is an integer greater than 1. The hydrino hydride ion is represented by $H^-(n = 1/p)$ or $H^-(1/p)$:

$$H\left[\frac{a_H}{p}\right] + e^- \rightarrow H^-(n = 1/p) \tag{5a}$$

$$H\left[\frac{a_H}{p}\right] + e^- \rightarrow H^-(1/p) \tag{5b}$$

The hydrino hydride ion is distinguished from an ordinary hydride ion comprising an ordinary hydrogen nucleus and two electrons having a binding energy of about 0.8 eV. The latter is hereafter referred to as "ordinary hydride ion" or "normal hydride ion" The hydrino hydride ion comprises a hydrogen nucleus including proteum, deuterium, or tritium, and two indistinguishable electrons at a binding energy according to Eq. (3).

Novel compounds are provided comprising one or more hydrino hydride ions and one or more other elements. Such a compound is referred to as a hydrino hydride compound.

Ordinary hydrogen species are characterized by the following binding energies (a) hydride ion, 0.754 eV ("ordinary hydride ion"); (b) hydrogen atom ("ordinary hydrogen atom"), 13.6 eV; (c) diatomic hydrogen molecule, 15.3 eV ("ordinary hydrogen molecule"); (d) hydrogen molecular ion, 16.3 eV ("ordinary hydrogen molecular ion"); and (e) $H_3^+$, 22.6 eV ("ordinary trihydrogen molecular ion"). Herein, with reference to forms of hydrogen, "normal" and "ordinary" are synonymous.

According to a further embodiment of the invention, a compound is provided comprising at least one increased binding energy hydrogen species such as (a) a hydrogen atom having a binding energy of about $\frac{13.6\ eV}{\left(\frac{1}{p}\right)^2}$, preferably within ±10%,, more preferably ±5%, where p is an integer, preferably an integer from 2 to 137; (b) a hydride ion ($H^-$) having a binding energy of about

$$Binding\ Energy = \frac{\hbar^2\sqrt{s(s+1)}}{8\mu_e a_0^2\left[\frac{1+\sqrt{s(s+1)}}{p}\right]^2} - \frac{\pi\mu_0 e^2\hbar^2}{m_e^2}\left(\frac{1}{a_H^3} + \frac{2^2}{a_0^3\left[\frac{1+\sqrt{s(s+1)}}{p}\right]^3}\right)$$

, preferably within ±10%, more preferably ±5%, where p is an integer, preferably an integer from 2 to 24; (c) $H_4^+(1/p)$; (d) a trihydrino molecular ion, $H_3^+(1/p)$, having a binding energy of about $\frac{22.6}{\left(\frac{1}{p}\right)^2}\ eV$ preferably within ±10%, more preferably ±5%, where p is an integer, preferably an integer from 2 to 137; (e) a dihydrino having a binding energy of about $\frac{15.3}{\left(\frac{1}{p}\right)^2}\ eV$ preferably within ±10%, more preferably ±5%, where p is an integer, preferably and integer from 2 to 137; (f) a dihydrino molecular ion with a binding energy of about $\frac{16.3}{\left(\frac{1}{p}\right)^2}\ eV$ preferably within ±10%, more preferably ±5%, where p is an integer, preferably an integer from 2 to 137.

According to a further preferred embodiment of the invention, a compound is provided comprising at least one increased binding energy hydrogen species such as (a) a dihydrino molecular ion having a total energy of

$$E_T = -p^2\left\{\frac{e^2}{8\pi\varepsilon_o a_H}(4\ln 3-1-2\ln 3)\left[1+p\sqrt{\frac{2\hbar\sqrt{\frac{\frac{2e^2}{4\pi\varepsilon_o(2a_H)^3}}{m_e}}}{m_ec^2}}\right]-\frac{1}{2}\hbar\sqrt{\frac{k}{\mu}}\right\} \quad (6)$$

$$= -p^2 16.13392\ eV - p^3 0.118755\ eV$$

preferably within ±10%, more preferably ±5%, where $p$ is an integer, $\hbar$ is Planck's constant bar, $m_e$ is the mass of the electron, $c$ is the speed of light in vacuum, $\mu$ is the reduced nuclear mass, and $k$ is the harmonic force constant solved previously [R. L. Mills, "The Nature of the Chemical Bond Revisited and an Alternative Maxwellian Approach", submitted. Posted at http://www.blacklightpower.com/pdf/technical/H2PaperTableFiguresCaptions111303.pdf which is incorporated by reference] and (b) a dihydrino molecule having a total energy of

$$E_T = -p^2\left\{\frac{e^2}{8\pi\varepsilon_o a_0}\left[\left(2\sqrt{2}-\sqrt{2}+\frac{\sqrt{2}}{2}\right)\ln\frac{\sqrt{2}+1}{\sqrt{2}-1}-\sqrt{2}\right]\left[1+p\sqrt{\frac{2\hbar\sqrt{\frac{\frac{e^2}{4\pi\varepsilon_o a_0^3}}{m_e}}}{m_ec^2}}\right]-\frac{1}{2}\hbar\sqrt{\frac{k}{\mu}}\right\}$$

$$= -p^2 31.351\ eV - p^3 0.326469\ eV \quad (7)$$

preferably within ±10%, more preferably ±5%, where $p$ is an integer and $a_o$ is the Bohr radius.

According to one embodiment of the invention wherein the compound comprises a negatively charged increased binding energy hydrogen species, the compound further comprises one or more cations, such as a proton, ordinary $H_2^+$, or ordinary $H_3^+$.

A method is provided for preparing compounds comprising at least one increased binding energy hydride ion. Such compounds are hereinafter referred to as "hydrino hydride compounds". The method comprises reacting atomic hydrogen with a catalyst having a net enthalpy of reaction of about $\frac{m}{2}\cdot 27\ eV$, where m is an integer greater than 1, preferably an integer less than 400, to produce an increased binding energy hydrogen

atom having a binding energy of about $\frac{13.6\ eV}{\left(\frac{1}{p}\right)^2}$ where $p$ is an integer, preferably an integer from 2 to 137. A further product of the catalysis is energy. The increased binding energy hydrogen atom can be reacted with an electron source, to produce an increased binding energy hydride ion. The increased binding energy hydride ion can be reacted with one or more cations to produce a compound comprising at least one increased binding energy hydride ion.

## II. SUMMARY OF THE INVENTION

An object of the present invention is to generate power and novel hydrogen species and compositions of matter comprising new forms of hydrogen via the catalysis of atomic hydrogen.

Another objective of the present invention is to generate a plasma and a source of light such as high energy light, extreme ultraviolet light and ultraviolet light, via the catalysis of atomic hydrogen.

Another objective of the present invention is to optimize the power balance by maximizing the output power from the hydrogen catalysis reaction while minimizing a pulsed or intermittent input power by controlling the parameters of the input power to initiate or at least partially maintain the plasma such as power density, pulse frequency, duty cycle, and peak and offset electric fields.

The above objectives and other objectives are achieved by the present invention comprising a plasma reactor to generate power and novel hydrogen species and compositions of matter comprising new forms of hydrogen via the catalysis of atomic hydrogen and to generate a plasma and a source of light such as high energy light, extreme ultraviolet light, and ultraviolet light, via the catalysis of atomic hydrogen. The reactor comprises a plasma forming energy cell for the catalysis of atomic hydrogen to form novel hydrogen species and compositions of matter comprising new forms of hydrogen, a source of catalyst for catalyzing the reaction of atomic hydrogen to form lower-energy hydrogen and release energy, a source of atomic hydrogen, and a source of intermittent or pulsed power to at least partially maintain the plasma. The cell comprises at least one of the group of a microwave cell, plasma torch cell, radio frequency (RF) cell, glow discharge cell, barrier electrode cell, plasma electrolysis cell, a pressurized gas cell,

filament cell or rt-plasma cell, and a combination of at least one of a glow discharge cell, a microwave cell, and an RF plasma cell that are disclosed in "Mills Prior Publications". The power balance is optimized by maximizing the output power from the hydrogen catalysis reaction while minimizing the input power by controlling the parameters of the input power to initiate or at least partially maintain the plasma such as the power density, pulse frequency, duty cycle, and peak and offset electric fields.

The intermittent or pulsed power source may provide a time period wherein the field is set to a desired strength by an offset DC, audio, RF, or microwave voltage or electric and magnetic fields. The field may be set to a desired strength during a time period by an offset DC, audio, RF, or microwave voltage or electric and magnetic fields that is below that required to maintain a discharge. The desired field strength during a low-field or nondischarge period may optimize the energy match between the catalyst and the atomic hydrogen. The intermittent or pulsed power source may further comprise a means to adjust the pulse frequency and duty cycle to optimize the power balance. The pulse frequency and duty cycle may be adjusted to optimize the power balance by optimizing the reaction rate versus the input power. The pulse frequency and duty cycle may be adjusted to optimize the power balance by optimizing the reaction rate versus the input power by controlling the amount of catalyst and atomic hydrogen generated by the discharge decay during the low-field or nondischarge period wherein the concentrations are dependent on the pulse frequency, duty cycle, and the rate of plasma decay.

## III. BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 is a schematic drawing of a plasma electrolytic cell reactor in accordance with the present invention;

FIGURE 2 is a schematic drawing of a gas cell reactor in accordance with the present invention;

FIGURE 3 is a schematic drawing of a gas discharge cell reactor in accordance with the present invention;

FIGURE 4 is a schematic drawing of a RF barrier electrode gas discharge cell reactor in accordance with the present invention;

FIGURE 5 is a schematic drawing of a plasma torch cell reactor in accordance with the present invention;

FIGURE 6 is a schematic drawing of another plasma torch cell reactor in accordance with the present invention, and

FIGURE 7 is a schematic drawing of a microwave gas cell reactor in accordance with the present invention.

## IV. DETAILED DESCRIPTION OF THE INVENTION

### 1. Plasma Reactor

A plasma cell to generate power and novel hydrogen species and compositions of matter comprising new forms of hydrogen via the catalysis of atomic hydrogen and to generate a plasma and a source of light such as high energy light, extreme ultraviolet light and ultraviolet light, via the catalysis of atomic hydrogen described in "Mills Prior Publications" may be at least one of the group of a microwave cell, plasma torch cell, radio frequency (RF) cell, glow discharge cell, barrier electrode cell, plasma electrolysis cell, a pressurized gas cell, filament cell or rt-plasma cell, and a combination of at least one of a glow discharge cell, a microwave cell, and an RF plasma cell. Each of these cells comprises: a plasma forming energy cell for the catalysis of atomic hydrogen to form novel hydrogen species and compositions of matter comprising new forms of hydrogen, a source catalyst to form solid, molten, liquid, or gaseous catalyst, a source of atomic hydrogen, and a source of intermittent or pulsed power to at least partially maintain the plasma. As used herein and as contemplated by the subject invention, the term "hydrogen", unless specified otherwise, includes not only proteum ($^1H$), but also deuterium ($^2H$) and tritium ($^3H$).

The following preferred embodiments of the invention disclose numerous property ranges, including but not limited to, pressure, flow rates, gas mixtures, voltage, current, pulsing frequency, power density, peak power, duty cycle, and the like, which are merely intended as illustrative examples. Based on the detailed written description, one skilled in the art would easily be able to practice this invention within other property ranges to produce the desired result without undue experimentation.

#### 1.1 Plasma Electrolysis Cell Hydride Reactor

A plasma electrolytic reactor of the present invention comprises an electrolytic cell including a molten electrolytic cell. The electrolytic cell 100 is shown generally in

FIGURE 1. An electric current is passed through the electrolytic solution 102 having a catalyst by the application of a voltage to an anode 104 and cathode 106 by the power controller 108 powered by the power supply 110. Ultrasonic or mechanical energy may also be imparted to the cathode 106 and electrolytic solution 102 by vibrating means 112. Heat can be supplied to the electrolytic solution 102 by heater 114. The pressure of the electrolytic cell 100 can be controlled by pressure regulator means 116 where the cell can be closed. The reactor further comprises a means 101 that removes the (molecular) lower-energy hydrogen such as a selective venting valve.

In an embodiment, the electrolytic cell is further supplied with hydrogen from hydrogen source 121 where the over pressure can be controlled by pressure control means 122 and 116. The reaction vessel may be closed except for a connection to a condensor 140 on the top of the vessel 100. The cell may be operated at a boil such that the steam evolving from the boiling electrolyte 102 can be condensed in the condensor 140, and the condensed water can be returned to the vessel 100. The lower-energy state hydrogen can be vented through the top of the condensor 140. In one embodiment, the condensor contains a hydrogen/oxygen recombiner 145 that contacts the evolving electrolytic gases. The hydrogen and oxygen are recombined, and the resulting water can be returned to the vessel 100.

A plasma forming electrolytic power cell and hydride reactor of the present invention for the catalysis of atomic hydrogen to form increased-binding-energy-hydrogen species and increased-binding-energy-hydrogen compounds comprises a vessel, a cathode, an anode, an electrolyte, a high voltage electrolysis power supply, and a catalyst capable of providing a net enthalpy of reaction of $m/2 \cdot 27.2 \pm 0.5\ eV$ where $m$ is an integer. Preferably $m$ is an integer less than 400. In an embodiment, the voltage is in the range of about 10 V to 50 kV and the current density may be high such as in the range of about 1 to 100 A/cm$^2$ or higher. In an embodiment, $K^+$ is reduced to potassium atom which serves as the catalyst. The cathode of the cell may be tungsten such as a tungsten rod, and the anode of cell of may be platinum. The catalyst of the cell may comprise at least one selected from the group of Li, Be, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Kr, Rb, Sr, Nb, Mo, Pd, Sn, Te, Cs, Ce, Pr, Sm, Gd, Dy, Pb, Pt, $He^+$, $Na^+$, $Rb^+$, $Fe^{3+}$, $Mo^{2+}$, $Mo^{4+}$, and $In^{3+}$. The catalyst of the cell of may be formed from a source of catalyst. A reductant or other element 160 extraneous to the operation of the cell may be

added to form increased binding energy hydrogen compounds.

1.2 Gas Cell Reactor

A gas cell reactor of the present invention is shown in FIGURE 2 comprises a reaction vessel 207 having a chamber 200 capable of containing a vacuum or pressures greater than atmospheric. A source of hydrogen 221 communicating with chamber 200 delivers hydrogen to the chamber through hydrogen supply passage 242. A controller 222 is positioned to control the pressure and flow of hydrogen into the vessel through hydrogen supply passage 242. A pressure sensor 223 monitors pressure in the vessel. A vacuum pump 256 is used to evacuate the chamber through a vacuum line 257.

A catalyst 250 for generating hydrino atoms can be placed in a catalyst reservoir 295. The reaction vessel 207 has a catalyst supply passage 241 for the passage of gaseous catalyst from the catalyst reservoir 295 to the reaction chamber 200. Alternatively, the catalyst may be placed in a chemically resistant open container, such as a boat, inside the reaction vessel.

The molecular and atomic hydrogen partial pressures in the reactor vessel 207, as well as the catalyst partial pressure, is preferably maintained in the range of about 10 millitorr to about 100 torr. Most preferably, the hydrogen partial pressure in the reaction vessel 207 is maintained at about 200 millitorr.

Molecular hydrogen may be dissociated in the vessel into atomic hydrogen by a dissociating material. The dissociating material may comprise, for example, a noble metal such as platinum or palladium, a transition metal such as nickel and titanium, an inner transition metal such as niobium and zirconium, or a refractory metal such as tungsten or molybdenum. The dissociating material may also be maintained at elevated temperature by temperature control means 230, which may take the form of a heating coil as shown in cross section in FIGURE 2. The heating coil is powered by a power supply 225. Molecular hydrogen may be dissociated into atomic hydrogen by application of electromagnetic radiation, such as UV light provided by a photon source 205. Molecular hydrogen may be dissociated into atomic hydrogen by a hot filament or grid 280 powered by power supply 285.

The catalyst vapor pressure is maintained at the desired pressure by controlling the temperature of the catalyst reservoir 295 with a catalyst reservoir heater 298 powered by a power supply 272. When the catalyst is contained in a boat inside the reactor, the catalyst

vapor pressure is maintained at the desired value by controlling the temperature of the catalyst boat, by adjusting the boat's power supply.

The gas cell hydride reactor further comprises an electron source 260 in contact with the generated hydrinos to form hydrino hydride ions. The cell may further comprise a getter or cryotrap 255 to selectively collect the lower-energy-hydrogen species and/or the increased-binding-energy hydrogen compounds.

1.3 Gas Discharge Cell Reactor

A gas discharge reactor of the present invention shown in FIGURE 3 comprises a gas discharge cell 307 comprising a hydrogen isotope gas-filled glow discharge vacuum vessel 313 having a chamber 300. A hydrogen source 322 supplies hydrogen to the chamber 300 through control valve 325 via a hydrogen supply passage 342. A catalyst is contained in catalyst reservoir 395. A voltage and current source 330 causes current to pass between a cathode 305 and an anode 320. The current may be reversible. In another embodiment, the plasma is generated with a microwave source such as a microwave generator.

The discharge voltage may be in the range of about 1000 to about 50,000 volts. The current may be in the range of about 1 $\mu$A to about 1 A, preferably about 1 mA. The discharge current may be intermittent or pulsed. In an embodiment, an offset voltage is provided that is between, about 0.5 to about 500 V. In another embodiment, the offset voltage is set to provide a field of about 0.1 V/cm to about 50 V/cm. Preferably, the offset voltage is set to provide a field between about 1 V/cm to about 10 V/cm. The peak voltage may be in the range of about 1 V to 10 MV. More preferably, the peak voltage is in the range of about 10 V to 100 kV. Most preferably, the voltage is in the range of about 100 V to 500 V. In an embodiment, the pulse frequency is of about 0.1 Hz to about 100 MHz. In another embodiment, the pulse frequency is faster than the time for substantial atomic hydrogen recombination to molecular hydrogen. Preferably the frequency is within the range of about 1 to about 200 Hz. In an embodiment, the duty cycle is about 0.1% to about 95%. Preferably, the duty cycle is about 1% to about 50%.

In another embodiment, the power may be applied as an alternating current (AC). The frequency may be in the range of about 0.001 Hz to 1 GHz. More preferably the frequency is in the range of about 60 Hz to 100 MHz. Most preferably, the frequency is in the range of about 10 to 100 MHz. The system may comprises two electrodes wherein

one or more electrodes are in direct contact with the plasma; otherwise, the electrodes may be separated from the plasma by a dielectric barrier. The peak voltage may be in the range of about 1 V to 10 MV. More preferably, the peak voltage is in the range of about 10 V to 100 kV. Most preferably, the voltage is in the range of about 100 V to 500 V.

In one embodiment of the gas discharge cell hydride reactor, the wall of vessel 313 is conducting and serves as the anode. In another embodiment, the cathode 305 is hollow such as a hollow, nickel, aluminum, copper, or stainless steel hollow cathode. In an embodiment, the cathode material may be a source of catalyst such as iron or samarium.

An embodiment of the gas discharge cell reactor where catalysis occurs in the gas phase utilizes a controllable gaseous catalyst. The gaseous hydrogen atoms for conversion to hydrinos are provided by a discharge of molecular hydrogen gas. The gas discharge cell 307 has a catalyst supply passage 341 for the passage of the gaseous catalyst 350 from catalyst reservoir 395 to the reaction chamber 300. The catalyst reservoir 395 is heated by a catalyst reservoir heater 392 having a power supply 372 to provide the gaseous catalyst to the reaction chamber 300. The catalyst vapor pressure is controlled by controlling the temperature of the catalyst reservoir 395, by adjusting the heater 392 by means of its power supply 372. The reactor further comprises a selective venting valve 301.

In another embodiment a chemically resistant open container, such as a tungsten or ceramic boat, positioned inside the gas discharge cell contains the catalyst. The catalyst in the catalyst boat is heated with a boat heater using by means of an associated power supply to provide the gaseous catalyst to the reaction chamber. Alternatively, the glow gas discharge cell is operated at an elevated temperature such that the catalyst in the boat is sublimed, boiled, or volatilized into the gas phase. The catalyst vapor pressure is controlled by controlling the temperature of the boat or the discharge cell by adjusting the heater with its power supply.

The gas discharge cell hydride reactor may further comprise an electron source 360 in contact with the generated hydrinos to form hydrino hydride ions.

### 1.4 Radio Frequency (RF) Barrier Electrode Discharge Cell Reactor

In an embodiment of the discharge cell reactor, at least one of the discharge electrodes is shielded by a dielectric barrier such as glass, quartz, Alumina, or ceramic in

order to provide an electric field with minimum power dissipation. A radio frequency (RF) barrier electrode discharge cell system 1000 of the present invention is shown in FIGURE 4. The RF power may be capacitively coupled. In an embodiment, the electrodes 1004 may be external to the cell 1001. A dielectric layer 1005 separates the electrodes from the cell wall 1006. The high driving voltage may be AC and may be high frequency. The driving circuit comprises a high voltage power source 1002 which is capable of providing RF and an impedance matching circuit 1003. The frequency is preferably in the range of about 100 Hz to about 10 GHz, more preferably, about 1 kHz to about 1 MHz, most preferably about 5-10 kHz. The voltage is preferably in the range of about 100 V to about 1 MV, more preferably about 1 kV to about 100 kV, and most preferably about 5 to about 10 kV.

### 1.5 Plasma Torch Cell Reactor

A plasma torch cell reactor of the present invention is shown in FIGURE 5. A plasma torch 702 provides a hydrogen isotope plasma 704 enclosed by a manifold 706 and contained in plasma chamber 760. Hydrogen from hydrogen supply 738 and plasma gas from plasma gas supply 712, along with a catalyst 714 for forming hydrinos and energy, is supplied to torch 702. The plasma may comprise argon, for example. The catalyst may be contained in a catalyst reservoir 716. The reservoir is equipped with a mechanical agitator, such as a magnetic stirring bar 718 driven by magnetic stirring bar motor 720. The catalyst is supplied to plasma torch 702 through passage 728. The catalyst may be generated by a microwave discharge. Preferred catalysts are $He^+$, $Ne^+$, or $Ar^+$ from a source such as helium, neon, or argon gas. The source of catalyst may be helium, helium, neon, neon-hydrogen mixture, or argon to form $He^+$, $He_2*$, $Ne_2*$, $Ne^+/H^+$ or $Ar^+$, respectively.

Hydrogen is supplied to the torch 702 by a hydrogen passage 726. Alternatively, both hydrogen and catalyst may be supplied through passage 728. The plasma gas is supplied to the torch by a plasma gas passage 726. Alternatively, both plasma gas and catalyst may be supplied through passage 728.

Hydrogen flows from hydrogen supply 738 to a catalyst reservoir 716 via passage 742. The flow of hydrogen is controlled by hydrogen flow controller 744 and valve 746. Plasma gas flows from the plasma gas supply 712 via passage 732. The flow of plasma gas is controlled by plasma gas flow controller 734 and valve 736. A mixture of plasma

gas and hydrogen is supplied to the torch via passage 726 and to the catalyst reservoir 716 via passage 725. The mixture is controlled by hydrogen-plasma-gas mixer and mixture flow regulator 721. The hydrogen and plasma gas mixture serves as a carrier gas for catalyst particles which are dispersed into the gas stream as fine particles by mechanical agitation. The aerosolized catalyst and hydrogen gas of the mixture flow into the plasma torch 702 and become gaseous hydrogen atoms and vaporized catalyst ions (such as $Rb^+$ ions from a salt of rubidium) in the plasma 704. The plasma is powered by a microwave generator 724 wherein the microwaves are tuned by a tunable microwave cavity 722. Catalysis may occur in the gas phase.

Hydrino atoms and hydrino hydride ions are produced in the plasma 704. Hydrino hydride compounds are cryopumped onto the manifold 706, or they flow into hydrino hydride compound trap 708 through passage 748. Trap 708 communicates with vacuum pump 710 through vacuum line 750 and valve 752. A flow to the trap 708 is effected by a pressure gradient controlled by the vacuum pump 710, vacuum line 750, and vacuum valve 752.

In another embodiment of the plasma torch cell hydride reactor shown in FIGURE 6, at least one of plasma torch 802 or manifold 806 has a catalyst supply passage 856 for passage of the gaseous catalyst from a catalyst reservoir 858 to the plasma 804. The catalyst 814 in the catalyst reservoir 858 is heated by a catalyst reservoir heater 866 having a power supply 868 to provide the gaseous catalyst to the plasma 804. The catalyst vapor pressure can be controlled by controlling the temperature of the catalyst reservoir 858 by adjusting the heater 866 with its power supply 868. The remaining elements of FIGURE 6 have the same structure and function of the corresponding elements of FIGURE 5. In other words, element 812 of FIGURE 6 is a plasma gas supply corresponding to the plasma gas supply 712 of FIGURE 5, element 838 of FIGURE 6 is a hydrogen supply corresponding to hydrogen supply 738 of FIGURE 5, and so forth.

In another embodiment of the plasma torch cell hydride reactor, a chemically resistant open container such as a ceramic boat located inside the manifold contains the catalyst. The plasma torch manifold forms a cell which can be operated at an elevated temperature such that the catalyst in the boat is sublimed, boiled, or volatilized into the gas phase. Alternatively, the catalyst in the catalyst boat can be heated with a boat heater having a power supply to provide the gaseous catalyst to the plasma. The catalyst vapor pressure can be controlled by controlling the temperature of the cell with a cell heater, or

by controlling the temperature of the boat by adjusting the boat heater with an associated power supply.

1.6. Microwave Gas Cell Hydride and Power Reactor

A microwave cell reactor of the present invention is shown in FIGURE 7. The reactor system of FIGURE 7 comprises a reaction vessel 601 having a chamber 660 capable of containing a vacuum or pressures greater than atmospheric. A source of hydrogen 638 delivers hydrogen to supply tube 642, and hydrogen flows to the chamber through hydrogen supply passage 626. The flow of hydrogen can be controlled by hydrogen flow controller 644 and valve 646. Plasma gas flows from the plasma gas supply 612 via passage 632. The flow of plasma gas can be controlled by plasma gas flow controller 634 and valve 636. A mixture of plasma gas and hydrogen can be supplied to the cell via passage 626. The mixture is controlled by hydrogen-plasma-gas mixer and mixture flow regulator 621. The plasma gas such as helium may be a source of catalyst such as $He^+$ or $He_2*$, argon may be a source of catalyst such as $Ar^+$, neon may serve as a source of catalyst such as $Ne_2*$, and neon-hydrogen mixture may serve as a source of catalyst such as $Ne^+/H^+$ and $Ne^+$. The source of catalyst and hydrogen of the mixture flow into the plasma and become catalyst and atomic hydrogen in the chamber 660.

The plasma may be powered by a microwave generator 624 wherein the microwaves are tuned by a tunable microwave cavity 622, carried by waveguide 619, and can be delivered to the chamber 660 though an RF transparent window 613 or antenna 615. Sources of microwaves known in the art are traveling wave tubes, klystrons, magnetrons, cyclotron resonance masers, gyrotrons, and free electron lasers. The waveguide or antenna may be inside or outside of the cell. In the latter case, the microwaves may penetrate the cell from the source through a window of the cell 613. The microwave window may comprise Alumina or quartz.

In another embodiment, the cell 601 is a microwave resonator cavity. In an embodiment, the cavity is at least one of the group of Evenson, Beenakker, McCarrol, and cylindrical cavity. In an embodiment, the cavity provides a strong electromagnetic field which may form a nonthermal plasma. Usually the nonthermal plasma temperature is in the range of 5,000 to 5,000,000 °C. Multiple sources of microwave power may be used simultaneously. In another embodiment, a multi slotted antenna such as a planar antenna

serves as the equivalent of multiple sources of microwaves such as dipole-antenna-equivalent sources. One such embodiment is given in Y. Yasaka, D. Nozaki, M. Ando, T. Yamamoto, N. Goto, N. Ishii, T. Morimoto, "Production of large-diameter plasma using multi-slotted planar antenna," Plasma Sources Sci. Technol., Vol. 8, (1999), pp. 530-533 which is incorporated herein by reference in its entirety.

The cell may further comprise a magnet such a solenoidal magnet 607 to provide an axial magnetic field wherein the magnetic field may be used to provide magnetic confinement. The microwave frequency is preferably in the range of about 1 MHz to about 100 GHz, more preferably in the range about 50 MHz to about 10 GHz, most preferably in the range of about 75 MHz $\pm$ 50 MHz or about 2.4 GHz $\pm$ 1 GHz.

A vacuum pump 610 may be used to evacuate the chamber 660 through vacuum lines 648 and 650. The cell may be operated under flow conditions with the hydrogen and the catalyst supplied continuously from catalyst source 612 and hydrogen source 638.

Hydrino hydride compounds can be cryopumped onto the wall 606, or they can flow into hydrino hydride compound trap 608 through passage 648. Alternatively dihydrino molecules may be collected in trap 608. Trap 608 communicates with vacuum pump 610 through vacuum line 650 and valve 652. A flow to the trap 608 can be effected by a pressure gradient controlled by the vacuum pump 610, vacuum line 650, and vacuum valve 652. In an embodiment, the microwave cell reactor further comprise a selective valve 618 for removal of lower-energy hydrogen products such as dihydrino molecules.

In another embodiment of the microwave cell reactor shown in FIGURE 7, the wall 606 has a catalyst supply passage 656 for passage of the gaseous catalyst 614 from a catalyst reservoir 658 to the plasma 604. The catalyst in the catalyst reservoir 658 can be heated by a catalyst reservoir heater 666 having a power supply 668 to provide the gaseous catalyst to the plasma 604. The catalyst vapor pressure can be controlled by controlling the temperature of the catalyst reservoir 658 by adjusting the heater 666 with its power supply 668.

In another embodiment of the microwave cell reactor, a chemically resistant open container such as a ceramic boat located inside the chamber 660 contains the catalyst. The reactor further comprises a heater that may maintain an elevated temperature. The cell can be operated at an elevated temperature such that the catalyst in the boat is sublimed, boiled, or volatilized into the gas phase. Alternatively, the catalyst in the catalyst boat can be heated with a boat heater having a power supply to provide the

gaseous catalyst to the plasma. The catalyst vapor pressure can be controlled by controlling the temperature of the cell with a cell heater, or by controlling the temperature of the boat by adjusting the boat heater with an associated power supply.

The molecular and atomic hydrogen partial pressures in the chamber 660, as well as the catalyst partial pressure, is preferably maintained in the range of about 1 mtorr to about 100 atm. Preferably the pressure is in the range of about 100 mtorr to about 1 atm, more preferably the pressure is about 100 mtorr to about 20 torr.

An exemplary plasma gas for the microwave cell reactor is argon. Exemplary flow rates are about 0.1 standard liters per minute (slm) hydrogen and about 1 slm argon. An exemplary forward microwave input power is about 1000 W. The flow rate of the plasma gas or hydrogen-plasma gas mixture such as at least one gas selected for the group of hydrogen, argon, helium, argon-hydrogen mixture, helium-hydrogen mixture is preferably about 0.000001-1 standard liters per minute per $cm^3$ of vessel volume and more preferably about 0.001-10 sccm per $cm^3$ of vessel volume. In the case of an argon-hydrogen or helium-hydrogen mixture, preferably helium or argon is in the range of about 99 to about 1 %, more preferably about 99 to about 95%. The power density of the source of plasma power is preferably in the range of about 0.01 W to about 100 W/$cm^3$ vessel volume.

### 1.7. Capacitively and Inductively Coupled RF Plasma Gas Cell Hydride and Power Reactor

A capacitively or inductively coupled radio frequency plasma (RF) plasma cell reactor of the present invention is also shown in FIGURE 7. The cell structures, systems, catalysts, and methods may be the same as those given for the microwave plasma cell reactor except that the microwave source may be replaced by a RF source 624 with an impedance matching network 622 that may drive at least one electrode and/or a coil. The RF plasma cell may further comprise two electrodes 669 and 670. The coaxial cable 619 may connect to the electrode 669 by coaxial center conductor 615. Alternatively, the coaxial center conductor 615 may connect to an external source coil which is wrapped around the cell 601 which may terminate without a connection to ground or it may connect to ground. The electrode 670 may be connected to ground in the case of the parallel plate or external coil embodiments. The parallel electrode cell may be according to the industry standard, the Gaseous Electronics Conference (GEC) Reference Cell or

modification thereof by those skilled in the art as described in G A. Hebner, K. E. Greenberg, "Optical diagnostics in the Gaseous electronics Conference Reference Cell, J. Res. Natl. Inst. Stand. Technol., Vol. 100, (1995), pp. 373-383; V. S. Gathen, J. Ropcke, T. Gans, M. Kaning, C. Lukas, H. F. Dobele, "Diagnostic studies of species concentrations in a capacitively coupled RF plasma containing $CH_4 - H_2 - Ar$," Plasma Sources Sci. Technol., Vol. 10, (2001), pp. 530-539; P. J. Hargis, et al., Rev. Sci. Instrum., Vol. 65, (1994), p. 140; Ph. Belenguer, L. C. Pitchford, J. C. Hubinois, "Electrical characteristics of a RF-GD-OES cell," J. Anal. At. Spectrom., Vol. 16, (2001), pp. 1-3 which are herein incorporated by reference in their entirety. The cell which comprises an external source coil such as a13.56 MHz external source coil microwave plasma source is as given in D. Barton, J. W. Bradley, D. A. Steele, and R. D. Short, "investigating radio frequency plasmas used for the modification of polymer surfaces," J. Phys. Chem. B, Vol. 103, (1999), pp. 4423-4430; D. T. Clark, A. J. Dilks, J. Polym. Sci. Polym. Chem. Ed., Vol. 15, (1977), p. 2321; B. D. Beake, J. S. G. Ling, G. J. Leggett, J. Mater. Chem., Vol. 8, (1998), p. 1735; R. M. France, R. D. Short, Faraday Trans. Vol. 93, No. 3, (1997), p. 3173, and R. M. France, R. D. Short, Langmuir, Vol. 14, No. 17, (1998), p. 4827 which are herein incorporated by reference in their entirety. At least one wall of the cell 601 wrapped with the external coil is at least partially transparent to the RF excitation. The RF frequency is preferably in the range of about 100 Hz to about 100 GHz, more preferably in the range about 1 kHz to about 100 MHz, most preferably in the range of about 13.56 MHz $\pm$ 50 MHz or about 2.4 GHz $\pm$ 1 GHz.

In another embodiment, an inductively coupled plasma source is a toroidal plasma system such as the Astron system of Astex Corporation described in US Patent No. 6,150,628 which is herein incorporated by reference in its entirety. The toroidal plasma system may comprise a primary of a transformer circuit. The primary may be driven by a radio frequency power supply. The plasma may be a closed loop which acts at as a secondary of the transformer circuit. The RF frequency is preferably in the range of about 100 Hz to about 100 GHz, more preferably in the range about 1 kHz to about 100 MHz, most preferably in the range of about 13.56 MHz $\pm$ 50 MHz or about 2.4 GHz $\pm$ 1 GHz.

2. Intermittent or Pulsed Input Power

The present invention comprises a power source to at least partially maintain the plasma in the cell. The power to maintain a plasma may be intermittent or pulsed.

Pulsing may be used to reduce the input power, and it may also provide a time period wherein the field is set to a desired strength by an offset DC, audio, RF, or microwave voltage or electric and magnetic fields which may be below those required to maintain a discharge. One application of controlling the field during the low-field or nondischarge period is to optimize the energy match between the catalyst and the atomic hydrogen. The pulse frequency and duty cycle may also be adjusted. An application of controlling the pulse frequency and duty cycle is to optimize the power balance. In an embodiment, this is achieved by optimizing the reaction rate versus the input power. The amount of catalyst and atomic hydrogen generated by the discharge decay during the low-field or nondischarge period. The reaction rate may be controlled by controlling the amount of catalyst generated by the discharge such as $Ar^+$ and the amount of atomic hydrogen wherein the concentration is dependent on the pulse frequency, duty cycle, and the rate of decay. In an embodiment, the pulse frequency is of about 0.1 Hz to about 100 MHz. In another embodiment, the pulse frequency is faster than the time for substantial atomic hydrogen recombination to molecular hydrogen. Based on anomalous plasma afterglow duration studies [R. Mills, T. Onuma, and Y. Lu, "Formation of a Hydrogen Plasma from an Incandescently Heated Hydrogen-Catalyst Gas Mixture with an Anomalous Afterglow Duration", Int. J. Hydrogen Energy, in press; R. Mills, "Temporal Behavior of Light-Emission in the Visible Spectral Range from a Ti-K2CO3-H-Cell", Int. J. Hydrogen Energy, Vol. 26, No. 4, (2001), pp. 327-332], preferably the frequency is within the range of about 1 to about 1000 Hz. In an embodiment, the duty cycle is about 0.001% to about 95%. Preferably, the duty cycle is about 0.1% to about 50%.

The frequency of alternating power may be within the range of about 0.001 Hz to 100 GHz. More preferably the frequency is within the range of about 60 Hz to 10 GHz. Most preferably, the frequency is within the range of about 10 MHz to 10 GHz. The system may comprises two electrodes wherein one or more electrodes are in direct contact with the plasma; otherwise, the electrodes may be separated from the plasma by a dielectric barrier. The peak voltage may be within the range of about 1 V to 10 MV. More preferably, the peak voltage is within the range of about 10 V to 100 kV. Most preferably, the voltage is within the range of about 100 V to 500 V. Alternatively, the system comprises at least one antenna to deliver power to the plasma.

In an embodiment of the plasma cell, the catalyst comprises at least one selected from the group of $He^+$, $Ne^+$, and $Ar^+$ wherein the ionized catalyst ion is generated from

the corresponding atom by a plasma created by methods such as a glow, inductively or capacitively coupled RF, or microwave discharge. Preferably the hydrogen pressure of the plasma cell is within the range of 1 mTorr to 10,000 Torr, more preferably the hydrogen pressure of the hydrogen microwave plasma is within the range of 10 mTorr to 100 Torr; most preferably, the hydrogen pressure of the hydrogen microwave plasma is within the range of 10 mTorr to 10 Torr.

A microwave plasma cell of the present invention for the catalysis of atomic hydrogen to form increased-binding-energy-hydrogen species and increased-binding-energy-hydrogen compounds comprises a vessel having a chamber capable of containing a vacuum or pressures greater than atmospheric, a source of atomic hydrogen, a source of microwave power to form a plasma, and a catalyst capable of providing a net enthalpy of reaction of $m/2 \cdot 27.2 \pm 0.5\ eV$ where $m$ is an integer, preferably $m$ is an integer less than 400. Sources of microwaves known in the art are traveling wave tubes, klystrons, magnetrons, cyclotron resonance masers, gyrotrons, and free electron lasers. The power may be amplified with an amplifier. The power may be delivered by at least one of a waveguide, coaxial cable, and an antenna. A preferred embodiment of pulsed microwaves comprises a magnetron with a pulsed high voltage to the magnetron or a pulsed magnetron current that may be supplied by a pulse of electrons from an electron source such as an electron gun.

The frequency of the alternating power may be within the range of about 100 MHz to 100 GHz. More preferably, the frequency is within the range of about 100 MHz to 10 GHz. Most preferably, the frequency is within the range of about 1 GHz to 10 GHz or about 2.4 GHz $\pm$ 1 GHz. In an embodiment, the pulse frequency is of about 0.1 Hz to about 100 MHz, preferably the frequency is within the range of about 10 to about 10,000 Hz, most preferably the frequency is within the range of about 100 to about 1000 Hz. In an embodiment, the duty cycle is about 0.001% to about 95%. Preferably, the duty cycle is about 0.1% to about 10%. The peak power density of the pulses into the plasma may be within the range of about 1 $W/cm^3$ to 1 $GW/cm^3$. More preferably, the peak power density is within the range of about 10 $W/cm^3$ to 10 $MW/cm^3$. Most preferably, the peak power density is within the range of about 100 $W/cm^3$ to 10 $kW/cm^3$. The average power density into the plasma may be within the range of about 0.001 $W/cm^3$ to 1 $kW/cm^3$. More preferably, the average power density is within the range of about 0.1

W/$cm^3$ to 100 W/$cm^3$. Most preferably, the average power density is within the range of about 1 W/$cm^3$ to 10 W/$cm^3$.

A capacitively and/or inductively coupled radio frequency (RF) plasma cell of the present invention for the catalysis of atomic hydrogen to form increased-binding-energy-hydrogen species and increased-binding-energy-hydrogen compounds comprises a vessel having a chamber capable of containing a vacuum or pressures greater than atmospheric, a source of atomic hydrogen, a source of RF power to form a plasma, and a catalyst capable of providing a net enthalpy of reaction of $m/2 \cdot 27.2 \pm 0.5\ eV$ where $m$ is an integer, preferably $m$ is an integer less than 400. The cell may further comprise at least two electrodes and an RF generator wherein the source of RF power may comprise the electrodes driven by the RF generator. Alternatively, the cell may further comprise a source coil which may be external to a cell wall which permits RF power to couple to the plasma formed in the cell, a conducting cell wall which may be grounded and a RF generator which drives the coil which may inductively and/or capacitively couple RF power to the cell plasma. The RF frequency is preferably within the range of about 100 Hz to about 100 MHz, more preferably within the range about 1 kHz to about 50 MHz, most preferably within the range of about 13.56 MHz ± 50 MHz. In an embodiment, the pulse frequency is of about 0.1 Hz to about 100 MHz, preferably the frequency is within the range of about 10 Hz to about 10 MHz, most preferably the frequency is within the range of about 100 Hz to about 1 MHz. In an embodiment, the duty cycle is about 0.001% to about 95%. Preferably, the duty cycle is about 0.1% to about 10%. The peak power density of the pulses into the plasma may be within the range of about 1 W/$cm^3$ to 1 GW/$cm^3$. More preferably, the peak power density is within the range of about 10 W/$cm^3$ to 10 MW/$cm^3$. Most preferably, the peak power density is within the range of about 100 W/$cm^3$ to 10 kW/$cm^3$. The average power density into the plasma may be within the range of about 0.001 W/$cm^3$ to 1 kW/$cm^3$. More preferably, the average power density is within the range of about 0.1 W/$cm^3$ to 100 W/$cm^3$. Most preferably, the average power density is within the range of about 1 W/$cm^3$ to 10 W/$cm^3$.

In another embodiment, an inductively coupled plasma source is a toroidal plasma system such as the Astron system of Astex Corporation described in US Patent No. 6,150,628 which is herein incorporated by reference in its entirety. The toroidal plasma system may comprise a primary of a transformer circuit. The primary may be driven by a

radio frequency power supply. The plasma may be a closed loop which acts at as a secondary of the transformer circuit. The RF frequency is preferably within the range of about 100 Hz to about 100 GHz, more preferably within the range about 1 kHz to about 100 MHz, most preferably within the range of about 13.56 MHz ± 50 MHz or about 2.4 GHz ± 1 GHz. In an embodiment, the pulse frequency is of about 0.1 Hz to about 100 MHz, preferably the frequency is within the range of about 10 Hz to about 10 MHz, most preferably the frequency is within the range of about 100 Hz to about 1 MHz. In an embodiment, the duty cycle is about 0.001% to about 95%. Preferably, the duty cycle is about 0.1% to about 10%. The peak power density of the pulses into the plasma may be within the range of about 1 $W/cm^3$ to 1 $GW/cm^3$. More preferably, the peak power density is within the range of about 10 $W/cm^3$ to 10 $MW/cm^3$. Most preferably, the peak power density is within the range of about 100 $W/cm^3$ to 10 $kW/cm^3$. The average power density into the plasma may be within the range of about 0.001 $W/cm^3$ to 1 $kW/cm^3$. More preferably, the average power density is within the range of about 0.1 $W/cm^3$ to 100 $W/cm^3$. Most preferably, the average power density is within the range of about 1 $W/cm^3$ to 10 $W/cm^3$.

In the case of the discharge cell, the discharge voltage may be within the range of about 1000 to about 50,000 volts. The current may be within the range of about 1 $\mu$A to about 1 A, preferably about 1 mA. The discharge current may be intermittent or pulsed. Pulsing may be used to reduce the input power, and it may also provide a time period wherein the field is set to a desired strength by an offset voltage which may be below the discharge voltage. One application of controlling the field during the nondischarge period is to optimize the energy match between the catalyst and the atomic hydrogen. In an embodiment, the offset voltage is between, about 0.5 to about 500 V. In another embodiment, the offset voltage is set to provide a field of about 0.1 V/cm to about 50 V/cm. Preferably, the offset voltage is set to provide a field between about 1 V/cm to about 10 V/cm. The peak voltage may be within the range of about 1 V to 10 MV. More preferably, the peak voltage is within the range of about 10 V to 100 kV. Most preferably, the voltage is within the range of about 100 V to 500 V. The pulse frequency and duty cycle may also be adjusted. An application of controlling the pulse frequency and duty cycle is to optimize the power balance. In an embodiment, this is achieved by optimizing the reaction rate versus the input power. The amount of catalyst and atomic

hydrogen generated by the discharge decay during the nondischarge period. The reaction rate may be controlled by controlling the amount of catalyst generated by the discharge such as $Ar^+$ and the amount of atomic hydrogen wherein the concentration is dependent on the pulse frequency, duty cycle, and the rate of decay. In an embodiment, the pulse frequency is of about 0.1 Hz to about 100 MHz. In another embodiment, the pulse frequency is faster than the time for substantial atomic hydrogen recombination to molecular hydrogen. Based on anomalous plasma afterglow duration studies [R. Mills, T. Onuma, and Y. Lu, "Formation of a Hydrogen Plasma from an Incandescently Heated Hydrogen-Catalyst Gas Mixture with an Anomalous Afterglow Duration", Int. J. Hydrogen Energy, in press; R. Mills, "Temporal Behavior of Light-Emission in the Visible Spectral Range from a Ti-K2CO3-H-Cell", Int. J. Hydrogen Energy, Vol. 26, No. 4, (2001), pp. 327-332], preferably the frequency is within the range of about 1 to about 200 Hz. In an embodiment, the duty cycle is about 0.1% to about 95%. Preferably, the duty cycle is about 1% to about 50%.

In another embodiment, the power may be applied as an alternating current (AC). The frequency may be within the range of about 0.001 Hz to 1 GHz. More preferably the frequency is within the range of about 60 Hz to 100 MHz. Most preferably, the frequency is within the range of about 10 to 100 MHz. The system may comprises two electrodes wherein one or more electrodes are in direct contact with the plasma; otherwise, the electrodes may be separated from the plasma by a dielectric barrier. The peak voltage may be within the range of about 1 V to 10 MV. More preferably, the peak voltage is within the range of about 10 V to 100 kV. Most preferably, the voltage is within the range of about 100 V to 500 V.

In the case of a barrier electrode plasma cell, the frequency is preferably within the range of about 100 Hz to about 10 GHz, more preferably, about 1 kHz to about 1 MHz, most preferably about 5-10 kHz. The voltage is preferably within the range of about 100 V to about 1 MV, more preferably about 1 kV to about 100 kV, and most preferably about 5 to about 10 kV.

In the case of the plasma electrolysis cell, the discharge voltage may be within the range of about 1000 to about 50,000 volts. The current into the electrolyte may be within the range of about 1 $\mu A/cm^3$ to about 1 $A/cm^3$, preferably about 1 $mA/cm^3$. In an embodiment, the offset voltage is below that which causes electrolysis such as within the range of about 0.001 to about 1.4 V. The peak voltage may be within the range of about 1

V to 10 MV. More preferably, the peak voltage is within the range of about 2 V to 100 kV. Most preferably, the voltage is within the range of about 2 V to 1 kV. In an embodiment, the pulse frequency is within the range of about 0.1 Hz to about 100 MHz. Preferably the frequency is within the range of about 1 to about 200 Hz. In an embodiment, the duty cycle is about 0.1% to about 95%. Preferably, the duty cycle is about 1% to about 50%.

In the case of the filament cell, the field from the filament may alternate from a higher to lower value during pulsing. The peak field may be within the range of about 0.1 V/cm to 1000 V/cm. Preferably, the peak field may be within the range of about 1 V/cm to 10 V/cm. The off-peak field may be within the range of about 0.1 V to 100 V/cm. Preferably, the off-peak field may be within the range of about 0.1 V to 1 V/cm. In an embodiment, the pulse frequency is within the range of about 0.1 Hz to about 100 MHz. Preferably the frequency is within the range of about 1 to about 200 Hz. In an embodiment, the duty cycle is about 0.1% to about 95%. Preferably, the duty cycle is about 1% to about 50%.

An exemplary plasma gas for the plasma reactor to generate power and novel hydrogen species and compositions of matter comprising new forms of hydrogen via the catalysis of atomic hydrogen is at least one of helium, neon, and argon corresponding to a source of the catalysts $He^+$, $Ne^+$, and $Ar^+$, respectively. In embodiments, hydrogen is flowed into the plasma cell separately or as a mixture with other plasma gases such as those that serve as sources of catalysts. The flow rate of the catalyst gas or hydrogen-catalyst gas mixture such as at least one gas selected for the group of hydrogen, argon, helium, argon-hydrogen mixture, helium-hydrogen mixture is preferably about 0.00000001-1 standard liters per minute per $cm^3$ of vessel volume and more preferably about 0.001-10 sccm per $cm^3$ of vessel volume. In the case of a helium-hydrogen, a neon-hydrogen, and an argon-hydrogen mixture, the helium, neon, or argon is in the range of about 99.99 to about .01 %, preferably in the range of about 99 to about 1 %, and more preferably about 99 to about 95%. In an embodiment, the remaining gas is hydrogen.

In any of the above reactors, an aspirator, atomizer, or nebulizer can be used to form an aerosol of the source of catalyst. If desired, the aspirator, atomizer, or nebulizer can be used to inject the source of catalyst or catalyst directly into the plasma.

If molybdenum is used as a cell material, the temperature of the operating cell is preferably maintained in the range of 0-1800 °C. If tungsten is used as a cell material, the

temperature of the operating cell is preferably maintained in the range of 0-3000 °C. If stainless steel is used as a cell material, the temperature of the operating cell is preferably maintained in the range of 0-1200 °C.